

[54] **FAST-ACTING FEEDFORWARD KICKER
CIRCUIT FOR USE WITH TWO SERIALY
CONNECTED INVERTERS**

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R27,305	3/1972	Polkinghorn et al.	307/251

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307/DIG. 4

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H03K 17/60

[58] Field of Search 307/205, 214, 251, 270,
307/304, DIG. 4

[57] **ABSTRACT**

A field-effect transistor serial inverter circuit is disclosed. Capacitive coupling is provided between the control electrode of a first inverter and the control electrode of a load transistor in a serially connected second inverter. The capacitor thereby couples the input to the load transistor of the second inverter, significantly reducing the transition delay time associated with the two series inverters, and also increasing the voltage level available at the output of the second inverter to substantially the same level as the supply voltage.

[56] **References Cited**

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20 Claims, 2 Drawing Figures

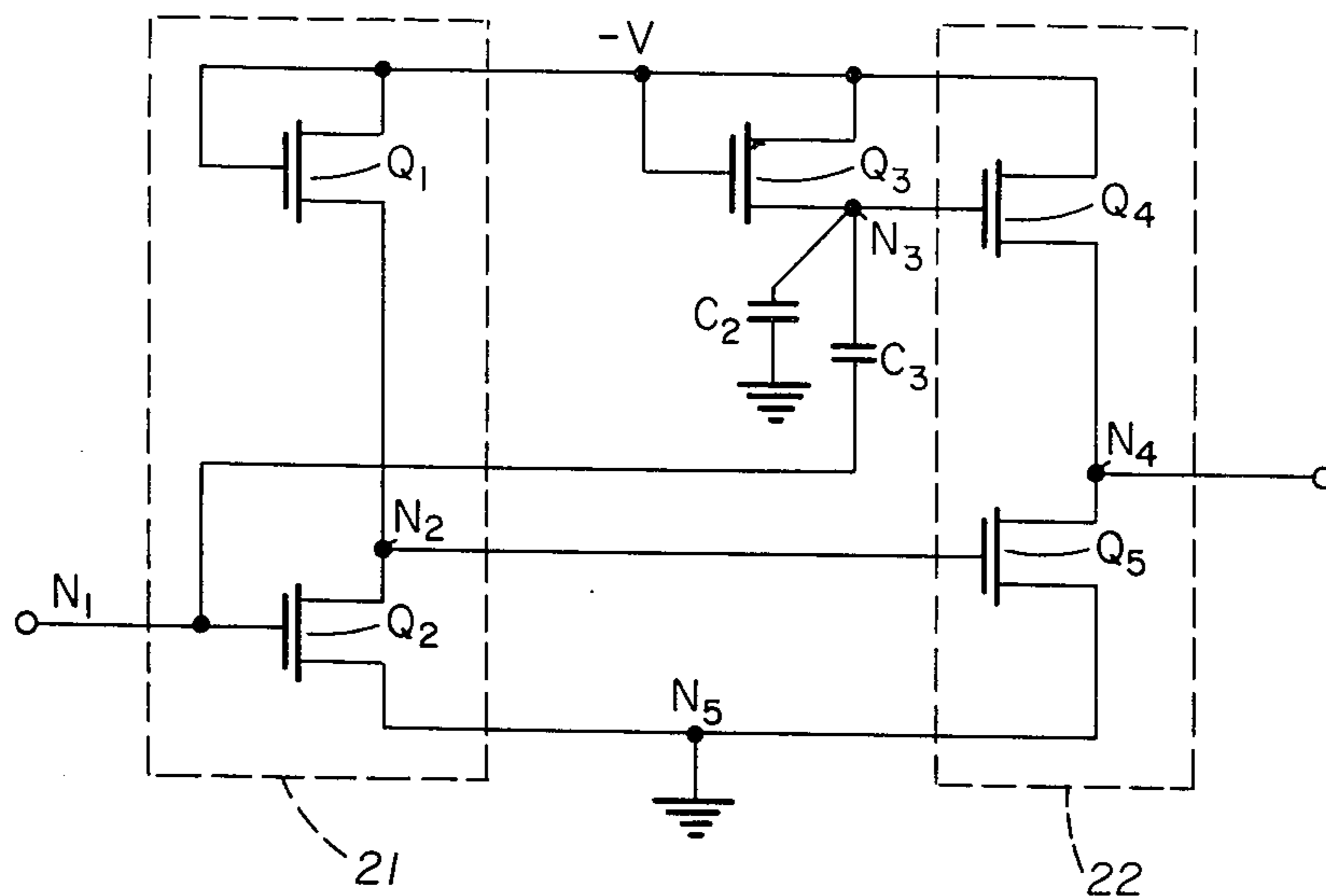


FIG. 1 / PRIOR ART

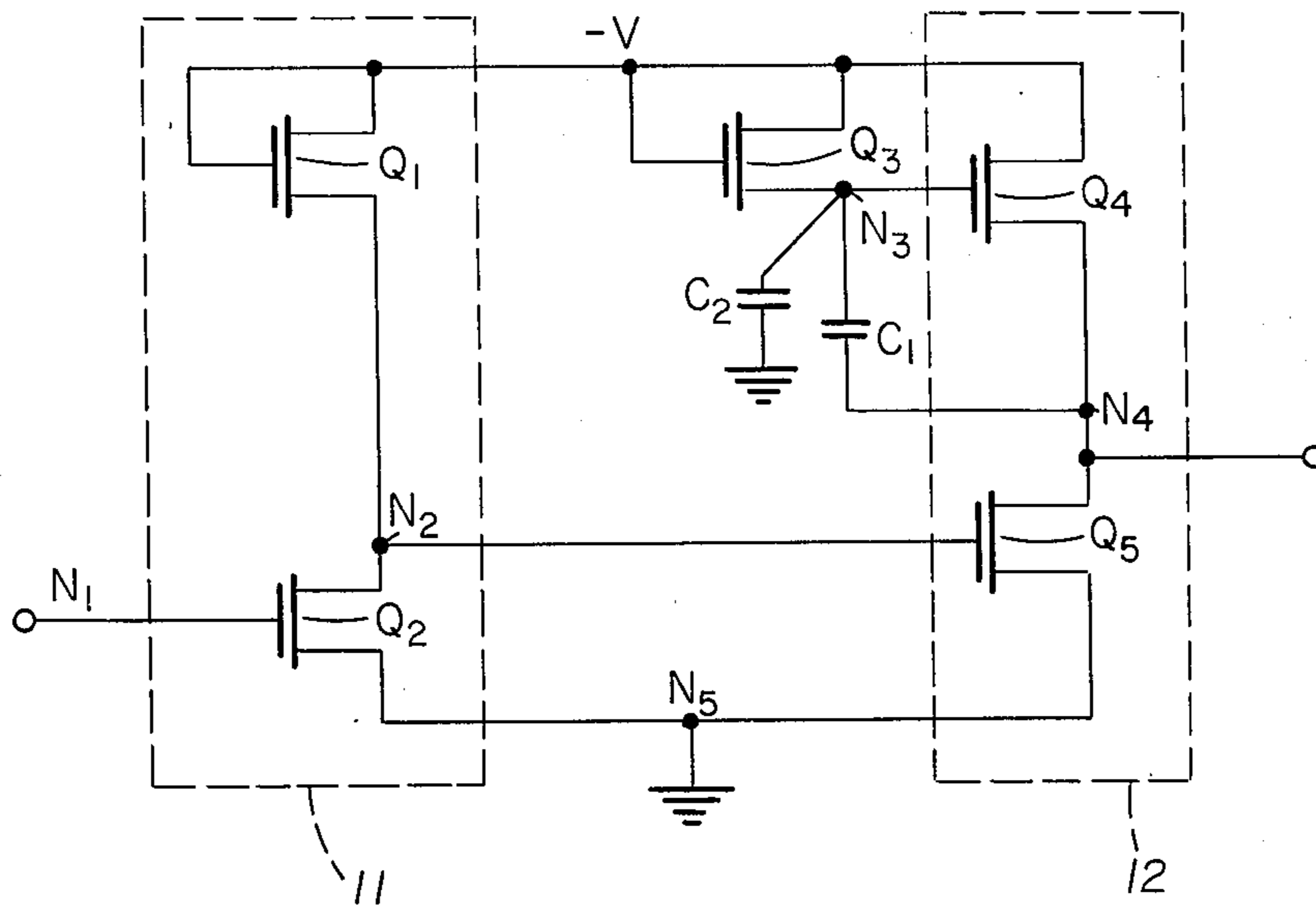
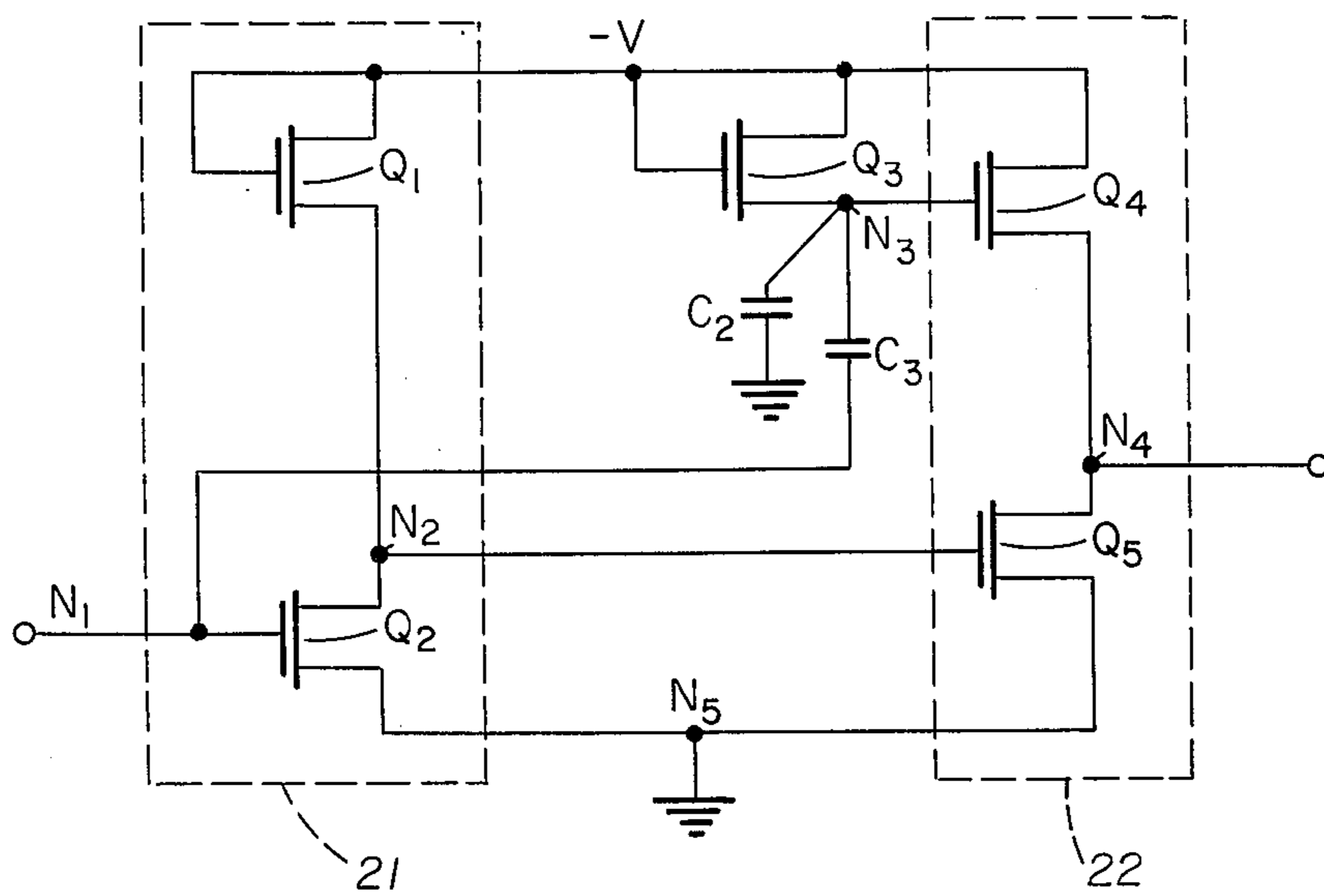


FIG. 2



FAST-ACTING FEEDFORWARD KICKER CIRCUIT FOR USE WITH TWO SERIALLY CONNECTED INVERTERS

BACKGROUND OF THE INVENTION

This invention relates to field-effect transistor logic circuitry and more particularly, to such circuits containing a pair of serial inverters.

The basic field-effect transistor, or FET, inverter consists essentially of a load FET and an input FET. The load FET serves essentially as a resistor connected between a supply voltage and a common node. The input FET whose drain-source path is connected between the common node and a circuit reference point acts as a switch. As is well-known, one particular type of field-effect transistor is the metal-oxide-semiconductor FET known generally as a MOSFET and all FETS referred to hereinafter are assumed P-channel MOSFET devices of the enhancement mode type, but it is understood that N-channel depletion mode MOSFET devices, or other types of transistors are equally applicable.

In the basic FET inverter the input is applied to the gate of the input FET, and a ground input, defined, for instance, as a logical 0, causes the input FET to be non-conductive; thus, the fixed voltage provided at the common node by the load FET represents the inversion of the input. A negative input sufficient to cause the input FET to become conductive is defined as the opposite logic state or logical 1. This input grounds the common node providing a logical 0. The output level is determined by the supply voltage so that the inverter can also provide amplification.

In some logic applications, two serially connected inverters are required, such as where the circuit functions as a preamplifier for a push-pull amplifier. All FET inverters exhibit an inherent delay and where a serial pair of inverters is utilized, both contribute to the total delay. Since the speed of the logic circuit is often of paramount importance, this combined delay is unacceptable in many circumstances. Therefore improvements in the speed of inverter operation have been suggested. For instance, an inverter may be provided with a bootstrap capacitor coupling the gate of its load FET to the common node. The resultant capacitive feedback causes the voltage of the gate of the load FET to approximately follow the voltage at the common node, thereby maintaining a nearly constant current through the load FET during the voltage transition at the common node. This speeds up the transition because there is no opposing current change as there would be without the bootstrapping. A single bootstrap inverter is disclosed, for instance, in FIG. 1 of R. W. Polkinghorn et al. Re 27,305, issued Mar. 14, 1972, and it may, of course, be serially coupled to another inverter as shown in FIG. 1 hereof.

However, transition speed of a pair of serial inverters in which the inverters are individually bootstrapped may still not be sufficient since the second of the inverters must await the change of state of the preceding inverter and this serial delay is not compensated for by the bootstrapping of either inverter. Furthermore, bootstrapping each inverter complicates the circuit since an isolating FET as well as the capacitor is required to bootstrap each inverter.

It is therefore an object of the present invention to provide a fast-acting logic circuit.

It is a further object to provide a fast-acting, serial inverter circuit which compensates for serial delay.

It is also an object to provide a fast-acting, amplifier which provides two serial inversions.

It is still a further object to provide a fast-acting serial inverter circuit utilizing field-effect transistors of the metal-oxide-semiconductor type.

SUMMARY OF THE INVENTION

In accordance with the present invention, capacitive coupling is provided between the input to the first of a pair of serially connected inverters and the load transistor of the second of the pair of inverters. This coupling provides feedforward of the input voltage to the control electrode of the load transistor of the second inverter. Since the common node of the second inverter is the circuit output and the voltage signal at this output is the twice-inverted form of the voltage signal at the circuit input, the feedforward voltage, which is unaffected by the delay of either inverter, anticipates the output voltage signal. This close correlation between the voltage at the control electrode of the load transistor of the second inverter and the forthcoming voltage at the common node overcomes the serial delay found in the prior art and, in fact, aids the transition at the common node. Thus, this feedforward kicker circuit provides faster operation of the two serial inverters than was previously possible. The feedforward voltage also boosts the output voltage substantially to the level of the supply voltage, as would the feedback voltage provided by bootstrapping the second inverter.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic diagram of a serial inverter utilizing the bootstrapping technique of the prior art to increase speed.

FIG. 2 is a schematic diagram of a serial pair of inverters in accordance with the present invention.

DETAILED DESCRIPTION

The circuit of FIG. 1 illustrates a serially connected pair of inverters 11 and 12 in which inverter 12 is bootstrapped in accordance with prior art technique. Inverter 11 consists of load FET Q_1 and input FET Q_2 . The drain-source path of Q_1 is connected between a source of supply voltage $-V$ and the common node N_2 of inverter 11. The gate of Q_1 is connected to a negative bias voltage which may be $-V$ as shown. Input FET Q_2 acts as a switch. Its drain-source path connects the common node N_2 and a voltage reference node N_5 , shown as ground. When the input signal voltage applied at node N_1 is zero (assumed to represent a logical 0), Q_2 is non-conductive or OFF and node N_2 is therefore near the supply voltage $-V$ representing a logical 1. When the input at node N_1 is sufficiently negative (representing a logical 1), Q_2 is ON causing node N_2 to go essentially to the potential of node N_5 , or ground, representative of a logical 0. Thus inverter 11 produces at node N_2 a signal which is logically opposite or inverted from the input signal at node N_1 .

In inverter 12, Q_4 and Q_5 perform similarly to Q_1 and Q_2 , respectively. The once-inverted signal at node N_2 is therefore reinverted to produce a twice-inverted signal at the output node N_4 . The load connected to node N_4 is not shown but is assumed to be capacitive although a resistive or inductive load would serve just as well.

The bootstrap capacitor C_1 is used to increase the speed of inverter 12. If the bootstrap arrangement con-

sisting of capacitor C_1 and isolating FET Q_3 , were not included in the circuit, the gate of load FET Q_4 would be connected directly to the fixed supply voltage $-V$, and the drain-source current, which is proportional to the square of the gate-source voltage, would therefrom be a function of the voltage at node N_2 (source voltage). Accordingly, when input FET Q_5 is OFF and the voltage at node N_4 is near $-V$, no significant current is drawn through FET Q_4 . When Q_5 is turning ON, it draws current from node N_4 in order to discharge node N_4 to ground (potential of node N_5). However, with the gate-source voltage of Q_4 increasing, the current through FET Q_4 increases and this increasing current must also pass to ground through Q_5 . Accordingly, the increase in Q_4 current opposes the transition at node N_4 and serves to slow the operation of the circuit. Conversely, if FET Q_5 is turning OFF, the voltage at node N_4 is changing from ground toward $-V$, and since the voltage at node N_4 is becoming increasingly more negative, the current through FET Q_4 is decreasing, consequently making less current available at node N_4 for charging the load and hence effecting the transition.

These inherent limitations upon the speed of transitions at node N_4 are reduced by the bootstrapping shown in FIG. 1. The gate of FET Q_4 is separated from supply voltage $-V$ by isolating FET Q_3 . For a voltage change at node N_4 of ΔV_{N_4} the change at node N_3 will be ΔV_{N_3} .

$$\left(\frac{C_1}{C_1 + C_2} \right)$$

due to the feedback via the voltage divider formed by capacitors C_1 and C_2 , where C_2 is a stray capacitance caused primarily by the geometry of the semiconductor structure. By design C_1 is made substantially larger than C_2 so that most of the voltage change at node N_4 is coupled to node N_3 . In this way, the gate-source voltage of FET Q_4 is kept nearly constant and the current through FET Q_4 is maintained relatively constant though the voltage at node N_4 is changing.

For example, when Q_5 turns ON and node N_4 starts to go to ground, this change in voltage is partially coupled to node N_3 (the gate of FET Q_4) by bootstrap capacitor C_1 . Thus, the gate-source voltage of FET Q_4 changes only slightly from its pre-transition value, and the current through Q_4 will likewise remain near its low pre-transition value. Therefore, FET Q_5 can discharge current from the load, not shown, without substantial opposition from the current through FET Q_4 . Hence, the bootstrapping speeds up the transition. Similarly, the fact that the voltage at node N_3 closely follows the voltage at node N_4 creates a faster logic transition when FET Q_5 is turning OFF.

This bootstrap coupling is normally made sufficient to cause node N_3 to be more than a threshold more negative than the supply voltage $-V$. Therefore, the source of FET Q_4 (node N_4) will reach the voltage at its drain ($-V$). Thus, the bootstrap coupling has the auxiliary effect of boosting the output voltage at node N_4 to substantially the level of the supply voltage for the logic state corresponding to logical 1.

While the positive feedback provided by bootstrapping does increase the speed of a single inverter, it does so by responding only after the transition at the common node has begun. This technique is incapable of reducing the serial delay, inherent in the operation of

two successive inverters and caused by the fact that one inverter drives another only after the first has made a transition.

Bootstrapping two serially connected inverters would, of course, increase overall speed, but a duplicate bootstrap circuit, including an isolating FET and a capacitor would be required for each inverter.

FIG. 2 illustrates serially connected inverters 21 and 22 corresponding essentially to the inverters 11 and 12 of FIG. 1 respectively, and all elements common to both figures are given the same numerical designation. Inverter 21 consisting of load FET Q_1 and input FET Q_2 is connected and operates identically to the previously described inverter 11. Q_1 functions as a resistor and Q_2 functions as a switch sensitive to the voltage applied to input node N_1 .

Inverter 22 consists of load FET Q_4 and input FET Q_5 . The drain-source path of load FET Q_4 connects the supply voltage $-V$ to node N_4 , and the drain-source path of input FET Q_5 connects node N_4 to the current reference node N_5 . The gate of FET Q_5 is connected to node N_2 , the output of inverter 21, and the gate of load FET Q_4 is connected to the supply voltage $-V$ through the drain-source path of isolating device FET Q_3 whose gate is also connected to $-V$. Stray capacitance C_2 associated with the gate of Q_4 is also shown.

Inverter 22 operates similarly to the previously described inverter 12. Thus the once-inverted signal at N_2 is applied to input FET Q_5 causing Q_5 to switch and produce a twice-inverted signal at the output node N_4 . However, there is no bootstrapping between node N_4 and node N_3 . Instead, in accordance with the invention, input node N_1 is capacitively coupled by capacitor C_3 to node N_3 (the gate of load FET Q_4). The input voltage at node N_1 is obviously unaffected by the delays associated with the inverters 21 and 22 and it is logically similar to the twice-inverted signal at output node N_4 .

This input signal which is fed forward from node N_1 to node N_3 actually anticipates the voltage change at N_4 . Thus, node N_3 leads node N_4 slightly and insures that the gate-source voltage of FET Q_4 changes in advance of and in aid of the transition at node N_4 . For example, if Q_5 is turning ON, node N_3 will receive "advance notice" since the twice-inverted signal being produced at node N_4 is logically the same as the signal at input node N_1 . This causes a decreasing current through FET Q_4 as FET Q_5 turns ON (node N_4 discharging to ground). Similarly, when Q_5 is about to turn OFF, the advance application of a logical 1 signal to node N_3 will cause the current through Q_4 to increase slightly in advance of and while Q_5 is turning OFF (node N_4 charging to $-V$).

The feedforward capacitor C_3 forms a voltage divider with the stray capacitance C_2 . Thus, a change in the voltage at node N_1 , ΔV_{N_1} , will produce ΔV_{N_3} .

$$\left(\frac{C_3}{C_3 + C_2} \right)$$

at node N_3 . Therefore, C_3 should be substantially larger than C_2 for adequate coupling. It is noted that one skilled in the art could, of course, make appropriate adjustment of values in order to control the speed of the circuit. However, it is obvious that if the feedforward coupling is large while the operations of the input transistors Q_2 and Q_5 are very slow, the increase in current through Q_4 in anticipation of Q_5 turning OFF,

could occur long before Q_5 begins to switch and this would result in a large transient current through Q_5 .

As in the bootstrap arrangement, the application of additional voltage to the gate of load FET Q_4 increases the voltage level available for the logical 1 state at the output of the second inverter 22 to substantially the same level as the supply voltage $-V$, and this may be of significantly greater magnitude than the corresponding voltage at the input node N_1 . But the major feature of the circuit is that the feedforward voltage, which is unaffected by the successive switch delays inherent in the combined operation of serial inverters 21 and 22, causes the overall circuit to function faster than the circuit of FIG. 1. The feedforward coupling via capacitor C_3 thus serves as a fast-acting kicker circuit for the serially connected inverted pair.

The FETS included in the above description may be any appropriate devices. The discussion has, however, assumed that they are field-effect transistors of the metaloxide semiconductor type and that P-channel enhancement mode elements are used. Alternative types of devices may, of course, be substituted, and when necessary, appropriate modifications of parameters such as biases would have to be made. In particular, load FET Q_1 could be bootstrapped, or it could be replaced by another type of transistor or by a two terminal diode. Also, input FETS Q_2 and Q_5 , which provide the input switching function, could be replaced by more complicated logic circuitry or by switch devices other than FETS such as, for example, bipolar transistors.

In addition, two supply voltages could be substituted for the single supply $-V$ shown, as disclosed in U.S. Pat. No. 3,845,324, issued to C. A. Feucht, Oct. 29, 1974. The drain of a given load FET would then be connected to one source and the gate, or the isolating transistor coupled to the gate, would be connected to the other more negative source.

In all cases it is to be understood that the above described arrangements are merely illustrative of a small number of the many possible applications of the principles of the present invention. Numerous and varied other arrangements in accordance with these principles may readily be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. A serial inverter circuit comprising:
 - a first and second inverter means, each having an input and an output, for producing at their outputs a logically inverted version of the signal applied to their respective inputs;
 - means for connecting the output of the first inverter means to the input of the second inverter means, whereby after a finite transition delay determined by the circuit values, the signal produced at the output of the second inverter means is logically identical to the signal applied to the input of the first inverter means; and
 - feedforward means for coupling the signal applied to the input of the first inverter means to the second inverter means to speed up all transitions of the signal at the output of the second inverter means made in response to a change of logical state of the signal applied to the input of the first inverter means.
2. A serial inverter circuit as claimed in claim 1 wherein the second inverter means includes:

a primary voltage source;
 a circuit reference node;
 an input device connected to the input of the second inverter means for selectively creating a conductive path between the circuit reference node and the output of the second inverter means in accordance with the signal applied thereto from the output of the first inverter means; and
 a load device having a first controlled electrode coupled to said primary voltage source, a second controlled electrode coupled to the output of the second inverter means, and a control electrode connected to said feedforward means.

3. A serial inverter circuit as claimed in claim 2 wherein the load device is a field-effect transistor having its drain-source path connected between the primary voltage source and the output of the second inverter means, and having means connected to its gate for isolating the gate from the primary voltage source; and

the feedforward means causing the voltage on the gate of the load device to always track the voltage at the input of the first inverter means, and thereby anticipate the voltage at the output of the second inverter means.

4. The serial inverter circuit as claimed in claim 2 wherein the feedforward means includes a capacitive coupling between the input of the first inverter means and the control electrode of the load device of the second inverter means.

5. A serial inverter circuit as claimed in claim 3 wherein the isolating means is a field-effect transistor having a first controlled electrode connected to the gate of the load device and having a second controlled electrode connected to a second voltage source, said isolating transistor being maintained in a conductive state.

6. A serial inverter circuit as claimed in claim 5 wherein the isolating field-effect transistor has a control electrode connected to said second voltage source, said second voltage source being the same as the primary voltage source.

7. A serial inverter circuit as claimed in claim 3 wherein the input device of the second inverter means is a field-effect transistor having its drain-source path connected between the circuit reference node and the output of the second inverter means and its gate electrode connected to the output of the first inverter means.

8. A serial inverter circuit as claimed in claim 7 wherein the input field-effect transistor and the load field-effect transistor are of the metal-oxide-semiconductor type.

9. A serial inverter circuit as claimed in claim 2 wherein the first inverter means includes an input field-effect transistor having its drain-source path connected between the circuit reference node and the output of the first inverter means, and having its gate connected to the input of the first inverter means; and

10. A serial inverter circuit as claimed in claim 9 wherein the voltage level of the primary voltage source is selected so that the voltage level at the output of the second inverter means is greater in magnitude than the voltage level of the logically identical signal at the input of the first inverter means for at least one logic state.

11. A serial inverter circuit of the type having:

a first and second inverter means, each having an input and an output, for producing at their outputs logically inverted versions of the signal applied to their respective inputs;

means for connecting the output of the first inverter means to the input of the second inverter means, whereby after a finite transition time determined by the circuit values, the signal produced at the output of the second inverter means is logically identical to the signal applied to the input of the first inverter means; characterized in that, the circuit further includes feedforward means for coupling the signal applied to the input of the first inverter means to the second inverter means such that the signal at the output of the second inverter means responds to all changes in logical state of the signal applied to the input of the first inverter means in a time less than said finite transition delay.

12. A serial inverter circuit as claimed in claim 11 wherein the second inverter means includes:

a primary voltage source;

a circuit reference node;

an input device connected to the input of the second inverter means for selectively creating a conductive path between the circuit reference node and the output of the second inverter means in accordance with the signal applied thereto from the output of the first inverter means; and

a load device having a first controlled electrode coupled to said primary voltage source, a second controlled electrode coupled to the output of the second inverter means, and a control electrode, said feedforward means being connected to the control electrode so that the voltage at the control electrode always tracks the voltage at the input of the first inverter means.

13. A serial inverter circuit as claimed in claim 12 wherein the load device is a field-effect transistor having its drain-source path connected between the primary voltage source and the output of the second inverter means, and having means connected to its gate for isolating the gate from the primary voltage source; and

the feedforward means causing the voltage on the gate of the load device to anticipate the voltage at the output of the second inverter means.

14. A serial inverter circuit as claimed in claim 13 wherein the feedforward means includes a capacitive coupling between the input of the first inverter means and the gate of the load device of the second inverter means.

15. A serial inverter circuit as claimed in claim 13 wherein the isolating means is a field-effect transistor having a first controlled electrode connected to the gate of the load device and having a second controlled electrode connected to a second voltage source, said isolating transistor being maintained in a conductive state.

16. A serial inverter circuit as claimed in claim 15 wherein the isolating field-effect transistor has a control electrode connected to said second voltage source.

17. A serial inverter circuit as claimed in claim 16 wherein said second voltage source is the same as the primary voltage source.

18. A serial inverter circuit as claimed in claim 13 wherein the input device of the second inverter means is a field-effect transistor having its drain-source path connected between the circuit reference node and the output of the second inverter means and its gate electrode connected to the output of the first inverter means.

19. A serial inverter circuit as claimed in claim 18 wherein the input field-effect transistor and the load field-effect transistor are of the metal-oxide-semiconductor type.

20. A serial inverter circuit having:
 an input;
 an output;
 a voltage source node;
 a circuit reference node;
 a first inverter formed by a first load field-effect transistor and a first input field-effect transistor, the first load transistor having its gate connected to the voltage source node and its drain-source path connected between the voltage source node and a common node, and the first input transistor having its drain-source path connected between the common node and the circuit reference node and its gate connected to the input;
 a second inverter formed by a second load field-effect transistor and a second input field-effect transistor, the second load transistor having its drain-source path connected between the voltage source node and the output, the second input transistor having its drain-source path connected between the output and the circuit reference node and its gate connected to the common node;
 an isolating field-effect transistor having its drain-source path connected between the voltage source node and the gate of the second load transistor, and having its gate connected to the voltage source node; and
 a capacitor connected between the input and the gate of the second load transistor.

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